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Geoefficiency and energy partitioning in CIR-driven and CME-driven storms

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ABSTRACT

Magnetic storms due to corotating interaction regions (CIRs) have been shown to elicit different responses in the magnetosphere than those prompted by other types of solar wind driving conditions such as coronal mass ejections (CMEs). In particular, CIRs provoke a much weaker response in ground magnetometer data (*Dst*), possibly indicative of a weaker ring current. They also last many days longer than the CME events, yet over these longer events they couple a great deal of energy, sometimes comparable to that involved in typically larger-*Dst* CME events. It may seem at first that the weaker driving of CIR events must result in proportionally weaker magnetospheric response, but that is not always the case. In this work we show that magnetic storms driven by CIRs deposit more energy in the ionosphere and ring current than would be expected from the electromagnetic energy input from the CIRs. They appear to be more geoefficient, in the sense that the ratio of the measured energy deposited (ring current, Joule heating, and auroral precipitation) to energy input is greater than that for CMEs.

1. Introduction and previous work

Energy flow in the magnetosphere is a subject that has intrigued researchers for many years (e.g., Turner, 2000; Baker et al., 2001; Weiss et al., 1992; Vichare et al., 2005). Lu et al. (1998) analyzed the energy output of the January 1997 magnetic storm. They used *Dst* to estimate ring current energy input and Assimilative Mapping of Ionospheric Electrodynamics (AMIE) calculations to estimate ionospheric Joule heating and auroral precipitation. Overall, in the January 10 and 11, 1997 case, Lu et al. (1998) estimated that the magnetosphere–ionosphere system dissipated an average of about 4.0×10^{11} W. Of this, 1.9×10^{11} W (or 48%) went into Joule heating, 1.2×10^{11} W (or 30%) went into ring current injection, and 0.9×10^{11} W (or 22%) went into auroral precipitation. They did not estimate the energy lost to plasmoids streaming down the magnetotail. A study by Knipp et al. (1998) showed that the November 1993 storm was an enormously geoeffective storm driven by a coronal mass ejection (CME) followed by a high-speed stream. In this extreme event, the researchers found that the ionospheric heating was $\sim 190 \times 10^{15}$ J, with 30% of that generated within 24 h of storm onset.

Gonzalez et al. (1989) tested several coupling functions to find the best match with *Dst* for intense ($Dst < -100$ nT) storms. They found that solar wind ram pressure played a role in ring current energization and that during the strong events they studied, there seemed to be a decoupling of the auroral response from the inner magnetospheric response for the solar wind-magnetosphere coupling functions they analyzed. The partitioning estimated from their Table 1 for the whole period was 60% to Joule heating, 23% to auroral precipitation, and 17% to the ring current.

Turner (2000) analyzed six storms in order to determine their energy input and output rates and energy partitioning. They used a form of *Dst*, modified to account for ground, tail, and magnetopause currents, in order to estimate the ring current energy and used AMIE data for ionospheric calculations of Joule heating and auroral precipitation, and also included an estimate for plasmoid ejection energy loss. In all cases, epsilon (Perreault and Akasofu, 1978; see Eq. (2)) was observed to correlate with the energy output, and in five of the six events epsilon was estimated to be larger than the output energy. The results of this analysis showed a clear dominance of ionospheric energy deposition over other processes. Joule heating alone accounted for around half of the observed output. The ring current contribution was less than in previous estimates, largely due to a reevaluation of the ring current strength compared to pressure-corrected *Dst* (Turner et al., 2000, 2001), and also due to the AMIE analysis suggesting a larger ionospheric loss. The authors concluded that the ring current energy was only about 10–15% of the total.

Another estimate of ionospheric energy deposition can be obtained from the polar cap (*PC*) index. Chun et al. (1999), based on comparisons with AMIE data assimilation results, have shown a quadratic relationship between the *PC* index and the hemispheric integrated Joule heating rate, and recent work

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Table 1
Energy for entire storm (medians).

	CIR (10^{16} J)	CME (10^{16} J)	P (u-test)
Input	6.38	8.07	0.02219
Ring current	0.416	0.539	0.02628
Joule heating	3.11	3.49	0.22689
Auroral precipitation	1.01	0.850	0.06468
Total output energy	4.45	5.10	0.39775
Efficiency	73.0%	62.7%	0.000744

shows a linear relationship between *PC* and electron precipitation. More recent work by Knipp et al. (2004) has shown a better fit to the data if both *PC* and *Dst* are used as inputs.

Because the Turner (2000) study covered only about two years of data, it was limited to a small portion of the solar cycle. Given that the frequency of appearance of solar wind structures varies widely over the solar cycle, with corotating interaction regions (CIRs) being more common during solar minimum, and CMEs being more common toward solar maximum (e.g., Tsurutani et al., 2006), this study was limited in its scope. Many researchers have observed differences in the dynamics of storms during times of different types of solar wind driving conditions (e.g., Borovsky and Denton, 2006), such as the existence of high-intensity long-duration continuous auroral activity (HILDCAA) events in the recovery phase of CIR-driven events (e.g., Tsurutani and Gonzalez, 1987; Tsurutani et al., 2006). On average, CIRs have less steady B_Z and higher bulk speed than non-CIR solar wind, and different B_Z characteristics from CMEs, and the resulting storms differ in some fundamental properties (see Zhang et al., 2006 for differences in solar wind parameters during solar minimum and solar maximum). Researchers have studied the ability of different types of solar wind structures to produce storms (see, e.g., Zhang et al., 2004). Echer and Gonzalez (2004) found that compound interplanetary structures were more geoeffective than isolated structures. In another study, Huttunen et al. (2002) looked at storms from 1996 to 1999. They found that almost all the intense (*Dst* < -100 nT) storms were associated with CMEs, but for the moderate storms, streams more often generated high Kp storms, while ejecta-related events more often drove stronger *Dst* changes. This could suggest that the relative impacts on the ring current and the ionosphere could vary by the type of solar wind driver. Gonzalez et al. (1999) found that complex interplanetary structures, including in rare circumstances the influence of subsequent CMEs, could drive particularly intense geomagnetic storms.

Turner et al. (2006) conducted a study of 42 storms and their geoeffectiveness. For these storms, clustered near the declining phase of the solar cycle, they found that CIR-driven storms were more efficient at coupling energy into the magnetosphere than CME storms. In other words, the ratio of measured energy output to estimated energy input varied with the type of solar wind driver. The authors used *Dst* to calculate ring current properties and used *PC* and *Dst*-based calculations, following the methods of Knipp et al. (2004) and Chun et al. (1999) to estimate ionospheric quantities. Lu (2006) also investigated this difference in coupling efficiency and came to the same conclusion, which is that CIR-driven events coupled energy more efficiently than CME-driven events. Her methodology for estimating the energy output varied significantly from the Turner et al. (2006) study, as Lu (2006) made use of AMIE ionospheric estimates, and she came to the same conclusion regarding the effectiveness of these solar wind structures. In this study, we follow the storm energy coupling efficiencies over an entire solar cycle and expand the data set to 280 total storms in order to show statistically the differences in energy coupling and energy partitioning.

2. Methodology

We focus our efforts on a total of 280 storms from 1995 to 2004, with 118 having CMEs as drivers, and 91 having CIRs (see Appendices A and B), while the remaining storms were not driven by either identified CIRs or CMEs. Storms were classified as being driven by CIRs or CMEs by Richardson et al. (2001, 2002; personal communication). For each storm, we use solar wind data from ACE and WIND to estimate the energy input and then estimate the energy dissipated via ring current, auroral precipitation, and Joule heating which we have summed and referred to here as energy output. From these, we calculate an energy coupling efficiency according to

$$\text{coupling efficiency} = \frac{\text{energy output}}{\text{energy input}} \tag{1}$$

where energy input is estimated by the integrated value of the epsilon parameter (Eq. (2)) for the duration of the storm, and energy output is the sum of ring current, auroral precipitation, and Joule heating for the duration of the storm. Each storm is considered to begin at the first decrease in Dst^* (Dst^* here denotes the solar wind dynamic pressure-corrected *Dst* index) and is considered completed when the Dst^* has recovered 80% from its lowest value. Our methodology, to be discussed below, closely parallels that in Turner et al. (2006).

2.1. Input energy

Accurate measurement of the total energy available to the magnetosphere from the solar wind at any given time is not possible. However, parameters exist that can help estimate this quantity. For this study, we use the epsilon parameter and the new Borovsky parameter, as described below. It is important to point out that, as useful as these parameters are, they only provide estimates of the energy available. Epsilon in particular is based on empirical data from some decades ago (Perreault and Akasofu, 1978), and therefore was calibrated to match what are now known to be underestimates of the magnetospheric energy output. For a more contemporary analysis of epsilon, see work by Koskinen and Tanskanen (2002). Therefore we take epsilon to be an estimate that allows some knowledge of when more energy is available and scales well with the energy output but does not necessarily capture the correct magnitude of energy input.

For each storm, we calculated the epsilon parameter (Perreault and Akasofu, 1978) to estimate the electromagnetic input power.

Epsilon is defined (in SI units) as

$$\varepsilon = \frac{4\pi}{\mu_0} v B^2 \sin^4\left(\frac{\theta}{2}\right) l_0^2 \tag{2}$$

where θ is the solar wind clock angle, $\theta = \tan^{-1}(|B_Y|/B_Z)$, and l_0 is a characteristic length scale of the magnetosphere, typically, as in this study, assumed to be $7R_E$, and μ_0 is the permeability of free space. B_Y and B_Z are the Y and Z components of the interplanetary magnetic field, respectively. R_E refers to a distance of one Earth radius. It should be noted that the epsilon parameter was derived empirically at a time with very little information about true energy deposition in the magnetosphere–ionosphere system. Therefore, while the form of epsilon can give a lot of information as to the relative amounts of energy being available to the magnetosphere, the absolute number is usually a significant underestimate, as will be demonstrated.